Dark Matter and Electroweak Baryogenesis

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based on works done in collaboration with:
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Outline

- **The Standard Model: its glory and shortcomes**
- **Evidence for Dark Matter and its possible origin**
- **The Puzzle of matter-antimatter asymmetry**

- **Baryogenesis at the Electroweak scale**
  - → **in the SM:** ruled out!
  - → **in the minimal SUSY extension of the SM:** constraints on the SUSY spectrum and extra CP violation

- **SUSY Dark matter and electroweak baryogenesis**
  - ✶ regions of neutralino relic density compatible with WMAP
  - ✶ experimental tests at colliders
  - ✶ direct dark matter detection

- **Conclusions**

The Standard Model: the pillar of particle physics

describes physical processes up to energies of about 100 GeV
(explains data collected in the past several years)
with very high precision (one part in a thousand)

Open questions in the Standard Model

- Source of Mass of fundamental particles.
- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).
- Nature of the Dark Matter, contributing to most of the matter energy of the Universe.
- Quantum Gravity and Unified Interactions.

Evidence for Dark Matter:

Visible stars do not account for enough mass to explain the rotation curves of galaxies

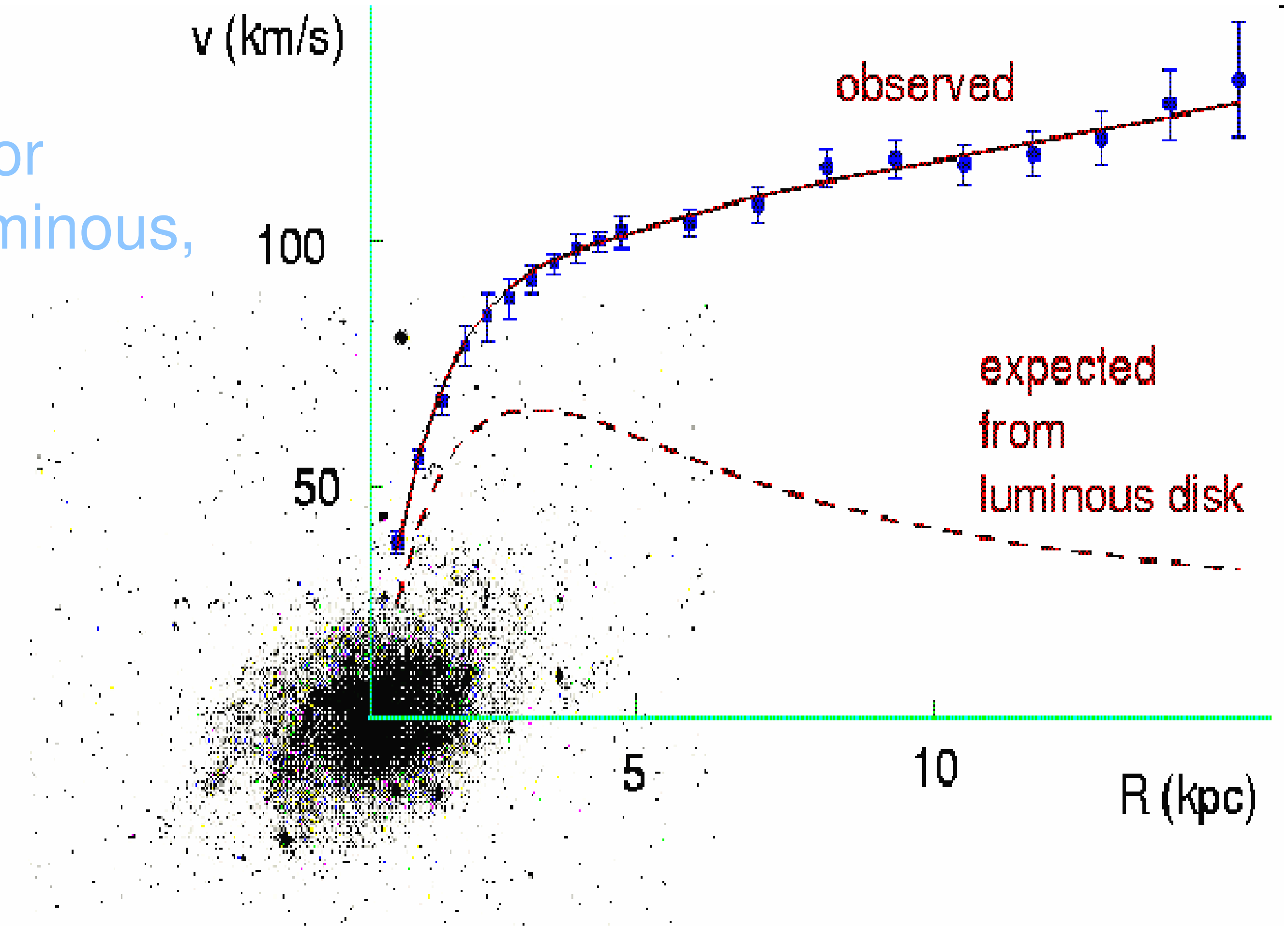
Gravity prediction: $$\frac{v^2}{r} = G_N \frac{M(r)}{r^2} \Rightarrow v^2 \propto \frac{1}{r}$$

Strong evidence for additional, non-luminous, source of matter:

⇩

Dark Matter

Zwicky , 1930s



Cosmic Microwave Background

WMAP measures the CMB and determines

$\Omega_M h^2 = 0.135 \pm 0.009$ $\Omega_B h^2 = 0.0224 \pm 0.0009$ $h = 0.71 \pm 0.04$

difference gives CDM energy density: $\Omega_{\mathrm{CDM}}\, h^2 = 0.1126 \pm^{0.0161}_{0.0181}$

What is Dark Matter? The SM has no suitable candidates

- leptons, hadrons: too little
- photons: $\Omega_{rad.} \approx 10^{-4}$
- neutrinos: too light
- W/Z bosons: too unstable
- Dark matter must be *something* beyond the SM!

Possible origin of Dark Matter

- Weakly interacting particles (WIMPS), with masses and interaction cross sections of order of the electroweak scale

$\longrightarrow$ most compelling alternative

Relic Density

- **To estimate WIMPs relic density, assume it was in thermal equilibrium in the early universe:**

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} Exp\left[-m/T\right]$$

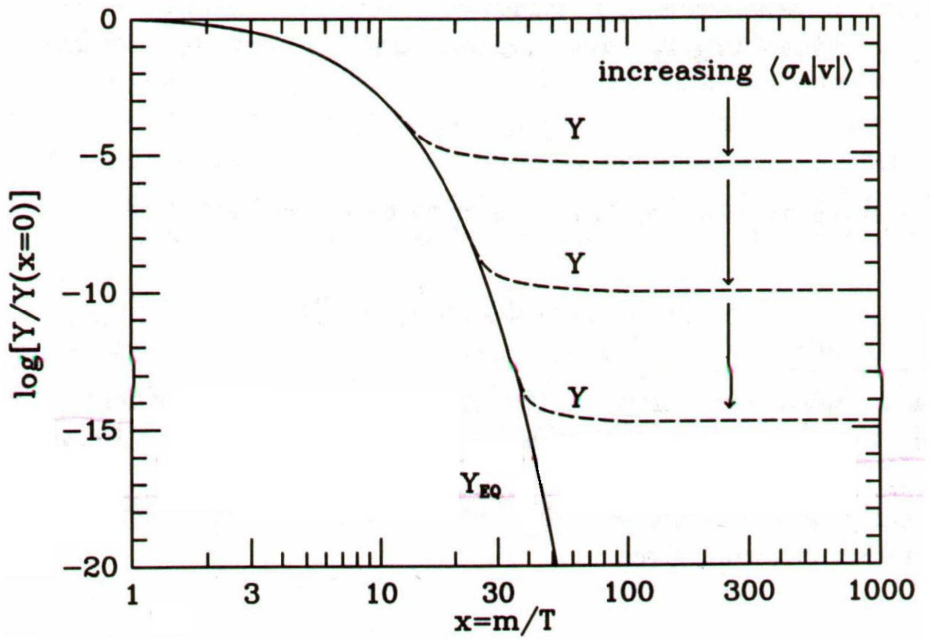
- Interactions with the relativistic plasma are efficient, and the WIMPs follow a Maxwell-Boltzmann distribution. **However, the universe is expanding, and once the density is small enough, they can no longer interact with one another, and fall out of equilibrium.**

Below the freeze–out temperature, the WIMPs density per co-moving volume is fixed

$$\frac{dY}{dx} = -\frac{\langle \sigma\, v \rangle}{H\ x}\, s\left(Y^2 - Y_{eq}^2\right)$$

with $Y = n/s$ and $x = m/T$

The key ingredient is the thermally annihilation cross section:
density is inversely proportional to it.

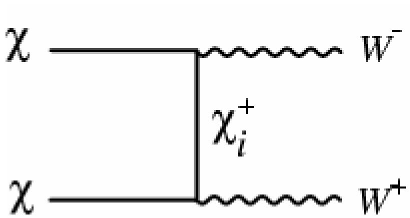


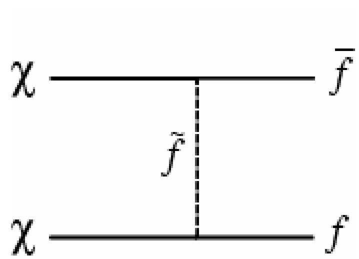
Kolb and Turner

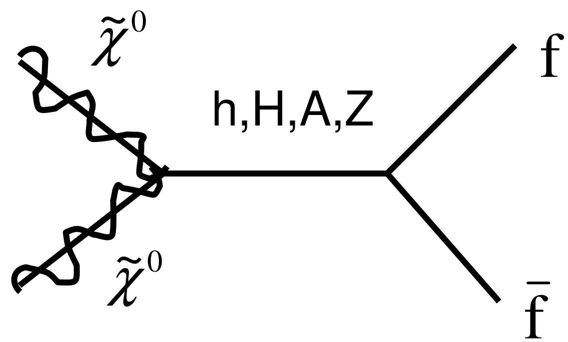
Supersymmetry:

with R parity discrete symmetry conserved $R_P = (-1)^{3B+L+2S}$
naturally provides a stable, neutral, dark matter candidate: the lightest neutralino $\tilde{\chi}^0$

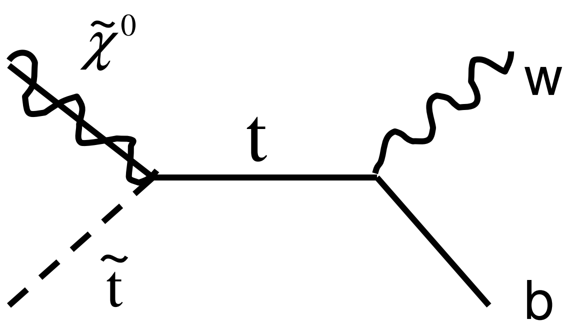
Many processes contribute to the neutralino annihilation cross section

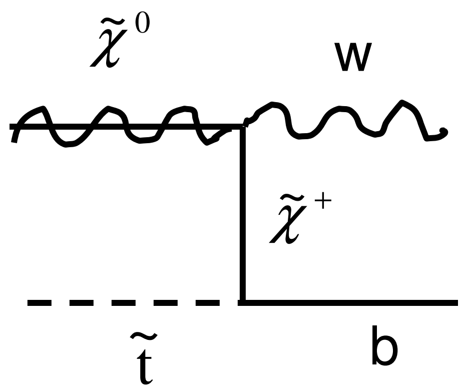






If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation





if stops NLSP

neutralino-stop

co-annihilation

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is mostly made of matter: $N_B >> N_{\overline{B}}$
- Anti-matter only seen in cosmic rays and particle physics accelerators

The rate observed in cosmic rays is consistent with secondary emission of antiprotons $N_{\overline{P}} \approx 10^{-4} \quad N_P$

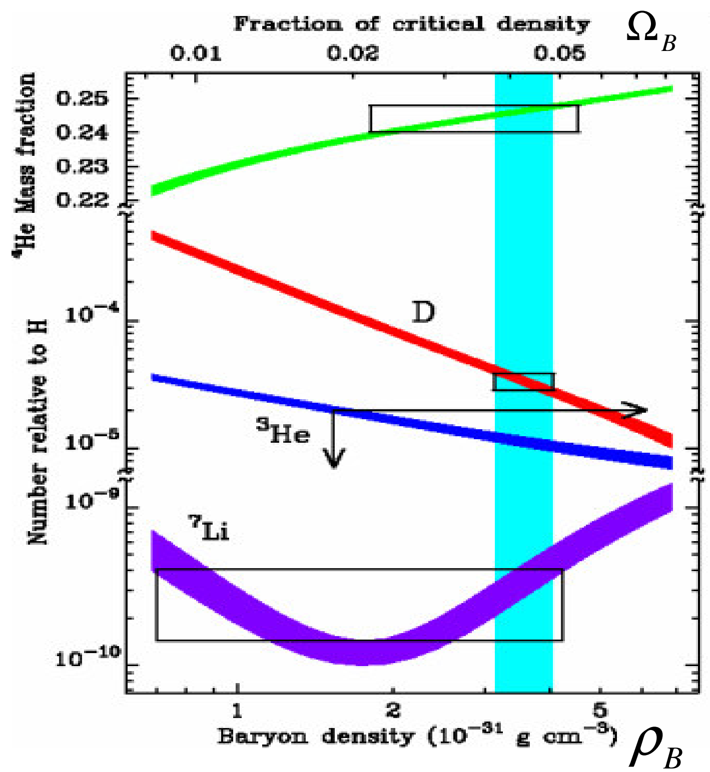
Information on the baryon abundance:

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$

- CMBR:

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$



Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8}\,\Omega_B h^2 \approx 6\ 10^{-10}$$

- In early universe $\mathrm{B}, \overline{\mathrm{B}}$ and γ's were equally abundant. $\mathrm{B}, \overline{\mathrm{B}}$ annihilated very efficiently. No net baryon number if B would be conserved at all times. What generated the small observed baryon antibaryon asymmetry ?

Sakharov's Requirements:

✦ Baryon Number Violation (any B conserving process: $N_B = N_{\overline{B}}$)

✦ C and CP Violation: $(N_B)_{\mathrm{L,R}} \neq (N_{\overline{B}})_{L,R}$

✦ Departure from thermal equilibrium

All three requirements fulfilled in the SM

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalous processes violate both B and L number, but preserve B-L. (Important for leptogenesis idea)

- *At T = 0, Baryon number violating processes exponentially suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_{\mathrm{W}})$$

- *At very high temperatures they are highly unsuppressed,*

$$\Gamma_{\Delta B \neq 0} \propto T$$

- *At Finite Temperature, instead, only Boltzman suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E_{sph}}(\mathrm{T}) / \mathrm{T})$$

with $\mathrm{E_{sph}} \cong 8\pi \, \mathrm{v(T)} / \mathrm{g}$ and v(T) the Higgs v.e.v.

Origin of Baryon asymmetry $\longrightarrow$ essentially two possibilities

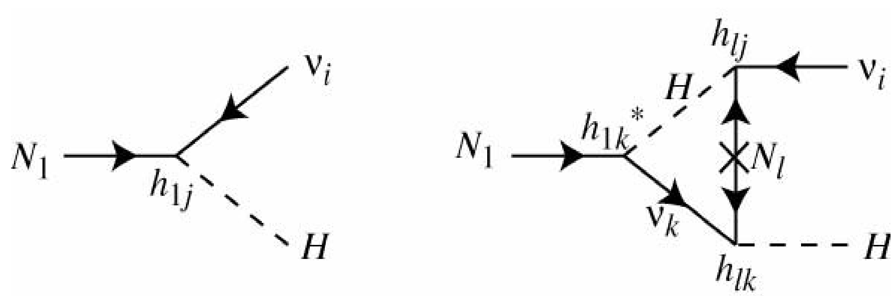
- **<u>Baryon asymmetry generated at high energies</u>**

$\longrightarrow$ through the decay of heavy particles, out of equilibrium, with

CP violation: to generate more B than anti B

B-L $\neq 0$: to avoid washout of generated B asymmetry via sphaleron processes

Leptogenesis: B number generated from L number plus anomaly interactions which convert L into B (Fukugita, Yanagida)



- Heavy, right-handed neutrinos decay out-of-equilibrium

- CP violating phases appear in the interference between the tree-level and one-loop amplitudes.

- Detailed calculation shows that lightest right handed neutrino mass should be $M_N \geq 10^{10}\,\mathrm{GeV}$ to obtain proper baryon asymmetry.

Needs heavy Majorana neutrinos, which are used in the standard explanation for neutrino masses: Seesaw Mechanism: small mass eigenvalue demands very large M_N

• Baryogenesis at the Electroweak Phase transition

• Start with B=L=0 at T>Tc

• CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.

• Net Baryon Number diffuse in the broken phase

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

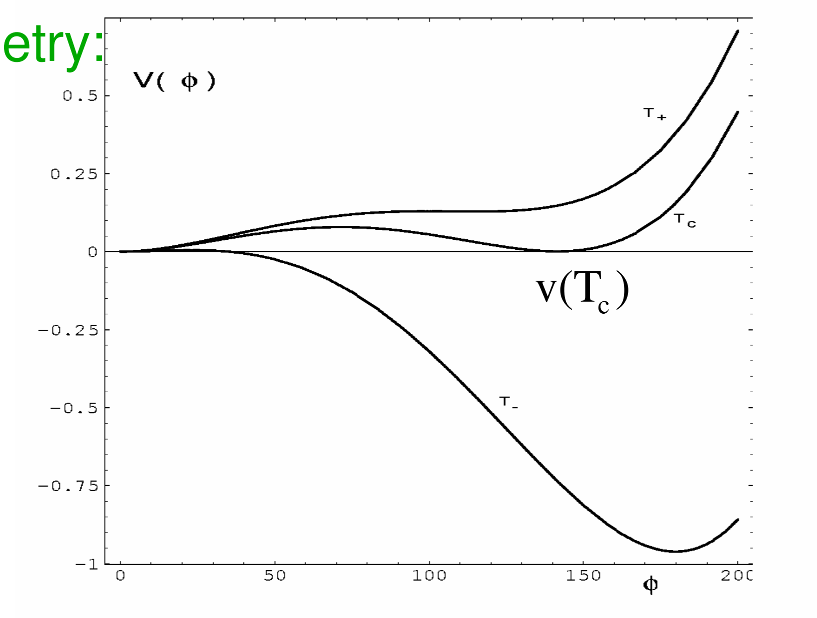
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(- \frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(- \frac{\mathrm{E_{sph}(T_c)}}{\mathrm{T_c}} \right) \right)$$

To preserve the generated baryon asymmetry:

strong first order phase transition:

$$v(T_c)/T_c > 1$$

Baryon number violating processes out of equilibrium in the broken phase



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V_{\mathrm{eff}}^{\mathrm{SM}} = -\, m^2(T)\, H^2 + E_{SM}\, T\, H^3 + \lambda(T)\, H^4$$

a cubic term is induced, proportional to the sum of the cube of all light boson particle masses

$$-\sum_b \frac{m_b^3(H)}{12\pi} T \quad \text{with} \quad m_b^2(H) \approx g_{bH}^2 H^2$$

In general: $m_b^2(H,T) = m_b^2 + g_{bH}^2 H^2 + \Pi(T)$ which can spoil the behaviour of the cubic term therefore jeorapdizing first order first transition

In the SM the only contribution comes from the transversal components of the gauge bosons

$$E_{SM} \approx \frac{2}{3}\left(\frac{2M_W^3 + M_z^3}{\sqrt{2\pi}\,v^3}\right)$$

→ hence a first order first transition occurs

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40\ \text{GeV} \Rightarrow \text{ ruled out by LEP!}$$

- **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

EW baryogenesis needs new light bosonic degrees of freedom with relevant couplings ot the Higgs. The Higgs boson should remain light

Supersymmetry provides a natural framework:

each SM chiral fermion has a complex scalar with identical quantum numbers (besides the spin)

relevant light bosons: SUSY partners of the top quark = stops

In the Minimal Supersymmetric extension of the Standard Model:

- two Higgs doublets H_1 and H_2 necessary ⟹ $\tan\beta = v_2 / v_1$
- Its neutral scalar components acquire v.e.v.'s: v_1, v_2

with $v^2 = v_1^2 + v_2^2 = 246\,\text{GeV}$ determined by gauge boson masses:

5 physical states remain: **2 CP-even h, H** **with mixing angle** α
1 CP-odd A **and a charged pair** $H^{\pm}$

If $m_A >> m_Z$ ⟹

decoupling limit

- **lightest Higgs has SM-like couplings and mass below 135 GeV**
- **other Higgs bosons heavy and roughly degenerate**

Light Stop Effects on Electroweak Baryogenesis

The left- and right-handed stops mix:

$$M_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{bmatrix}$$

with $\mathrm{X_t} = A_t - \dfrac{\mu^*}{\tan\beta}$

and $\mathrm{m_t} = h_t \, \mathrm{H_2} = h_t \sin\beta \;\phi$

Hierarchy in soft SUSY breaking param:

$\mathrm{m_Q^2} \gg \mathrm{m_U^2}$ $\Longrightarrow$ best fit to precision electroweak data

The lightest stop $\Longrightarrow$ $\mathrm{m_{\tilde{t}}^2 (T=0) \approx m_U^2 + D_R + m_t^2} \left(1 - \dfrac{X_t^2}{\mathrm{m_Q^2}} \right)$

has six degrees of freeedom and a coupling of order one to the Higgs

$$V_{eff}^{MSSM} = -m^2(\mathrm{T}) \;\; \phi^2 - \mathrm{T}\left[\mathrm{E_{SM}} \phi^3 + 2N_c \frac{(\mathrm{m_{\tilde{t}}^2} + \Pi_R(T))^{3/2}}{12\,\pi} \right] + \frac{\lambda(T)}{2} \phi^4$$

No stop contrib. to cubic term unless $\mathrm{m_U^2} + \Pi_R(T) \approx 0$, very light right-h. stop!

In the MSSM: $$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

one stop should be quite light and the stop mixing moderate to enhance E_{MSSM}

- For small stop mixing: $E_{MSSM} \approx 9\, E_{SM}$ hence $m_{h_{MSSM}}^{max.} \approx 3 m_{H_{SM}}^{max.} \approx 120\,\mathrm{GeV}$

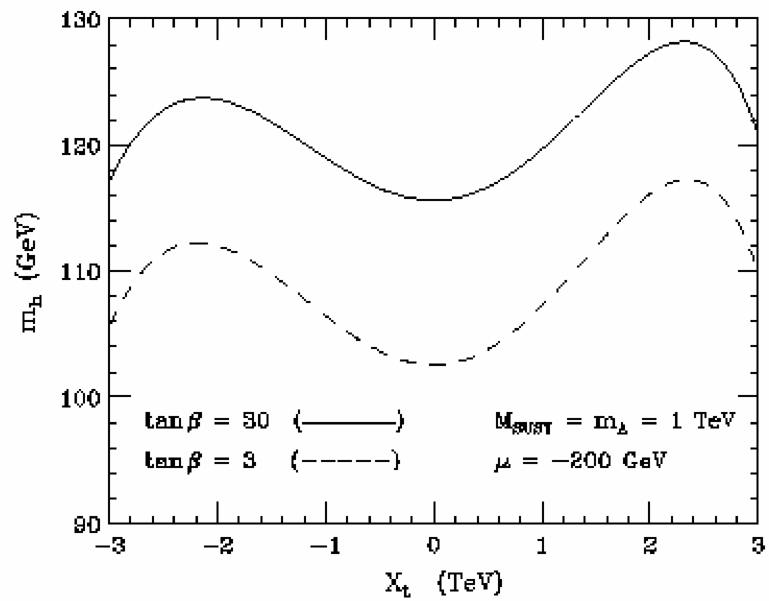
it can work!!

Present LEP bounds on the SM- like Higgs mass imply extra demands!

$$m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$$

- MSSM lightest Higgs mass depends crucialy on m_t^4, on the stop mixing X_t and logarithmically on the stop masses

$$m_h^2 \approx M_Z^2 \cos^2 2\beta +$$
$$\frac{3m_t^4}{8\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}_l}^2 m_{\tilde{t}_H}^2}{m_t^4}\right) + 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde{t}_H}^2}{m_{\tilde{t}_l}^2}\right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4}\right)\right]$$



hence $m_Q \geq 1\,\mathrm{TeV}$ and $X_t \geq 0.3 m_Q$ nedeed

Higgs and Stop mass constriants for Electroweak Baryogenesis

- ***Higgs masses up to 120 GeV***
- ***The lightest stop must have a mass below the to quark mass.***

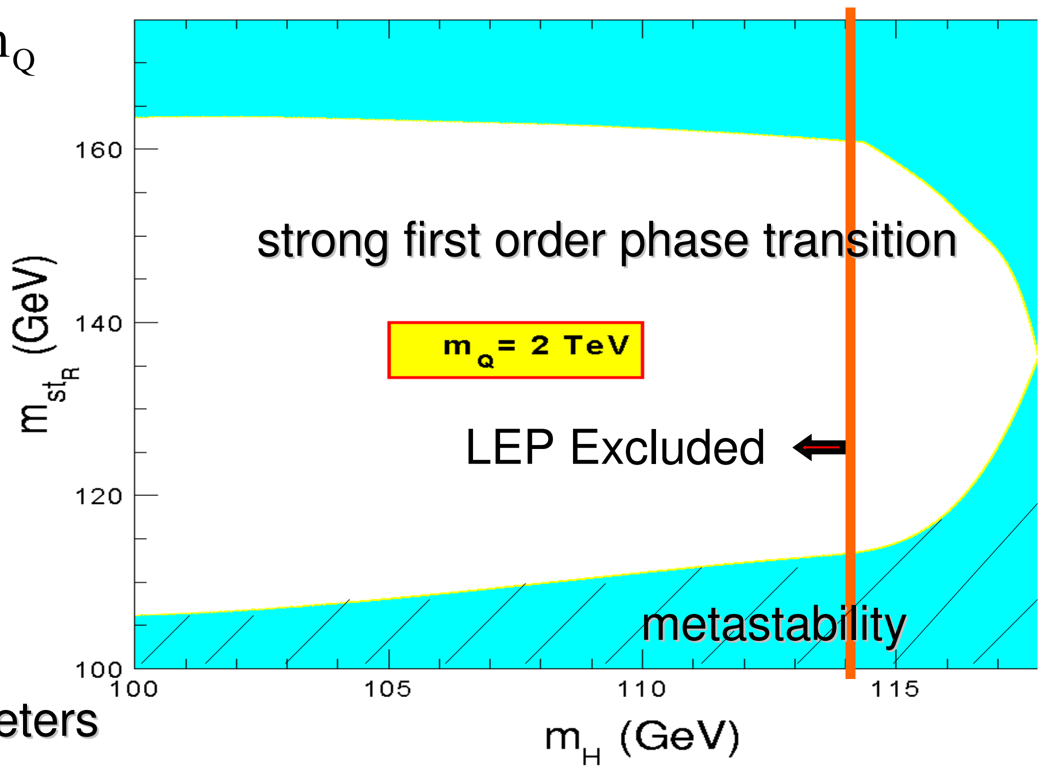
A same point in this plane corresponds to different values of the Higgs and stop param.: $\tan\beta,\ X_t,\ m_U$ and m_Q

$\tan\beta \geq 5,\ m_Q \geq 1\,\text{TeV}, X_t \geq 0.3\,m_Q$

$\Rightarrow$ lower values lead to too small Higgs mass

$m_U \approx 0, \quad X_t \leq 0.5\,m_Q$

$\Rightarrow$ to have a sufficiently strong first order first transition



conditions on the stop sector parameters secure vacuum stability

No color breaking minima

M.C, Quiros, Wagner

Computation of the baryon asymmetry

New CP violating phases in the stop and chargino sector are crucial
[for large values of m_Q, only the chargino –neutralino currents are relevant]

- Interaction with varying Higgs background in the bubble wall creates net neutral and charged Higgsino currents through CP-violating interactions

- Higgsino interactions with plasma creates an excess of left-handed anti-baryons (right-handed baryons)

- Left-handed baryon asymmetry is partially converted to lepton asymmetry via anomalous processes (weak sphalerons: net B violation)

- Baryon asymmetry diffuses into broken phase and gets frozen there since $v(T) / T > 1$

Assuming time relaxation of charge is large (no particle decays)

1. compute CP-violating currents
2. solve diffusion equations describing the above processes

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : $\tan\beta,\ m_A$
Chargino sector : mass param. $\mu,\ M_2$ with physical phase $\arg(\mu^* M_2)$

currents proportional to sin($\arg(\mu^* M_2)$), with resonant behavior for $M_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $\varepsilon_{ij} H_i \partial_\mu H_j = v^2(T)\, \partial_\mu \beta$

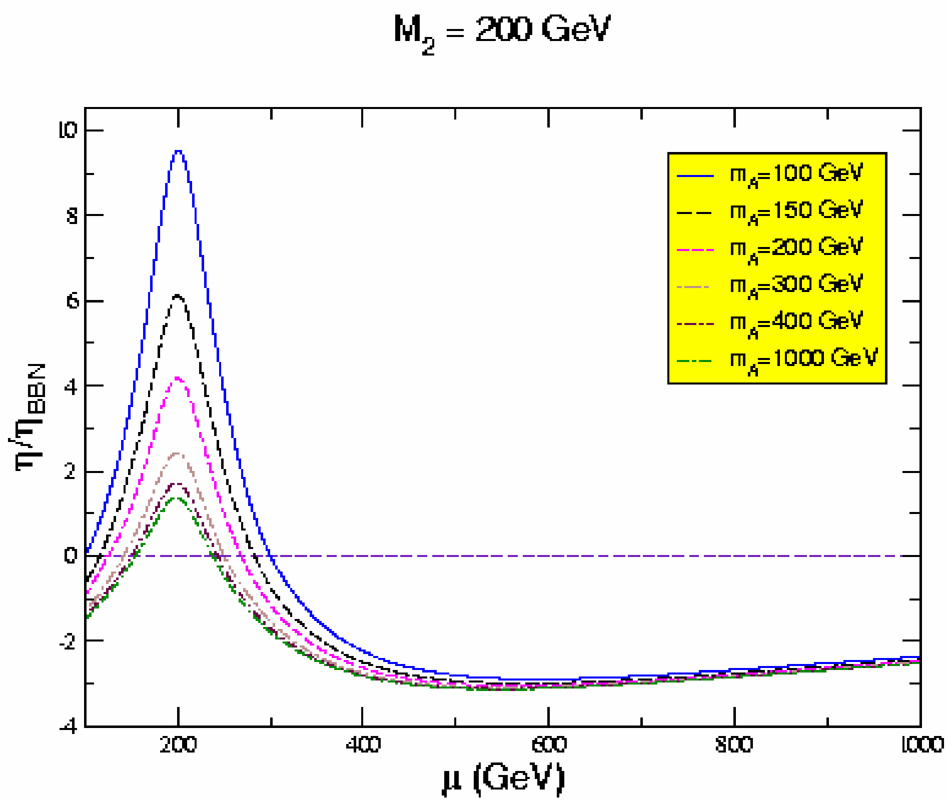
suppressed for large m_A and $\tan\beta$ due to $\Delta\beta$ dependence

★ $H_1 \partial_\mu H_2 + H_2 \partial_\mu H_1 = v^2 \cos(2\beta)\, \partial_\mu \beta + v\, \partial_\mu v \sin(2\beta)$

unsuppressed for large CP-odd masses

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.Carena, M.Quiros, M. Seco and C.W. '02



Gaugino and Higgsino masses of the order of the weak scale highly preferred

Results for maximal CP violation

$$\sin(\arg(\mu^* M_2)) = 1$$

<u>Baryon Asymmetry Enhanced for</u> ; $M_2 = |\mu|$ ***and smaller values of*** m_A

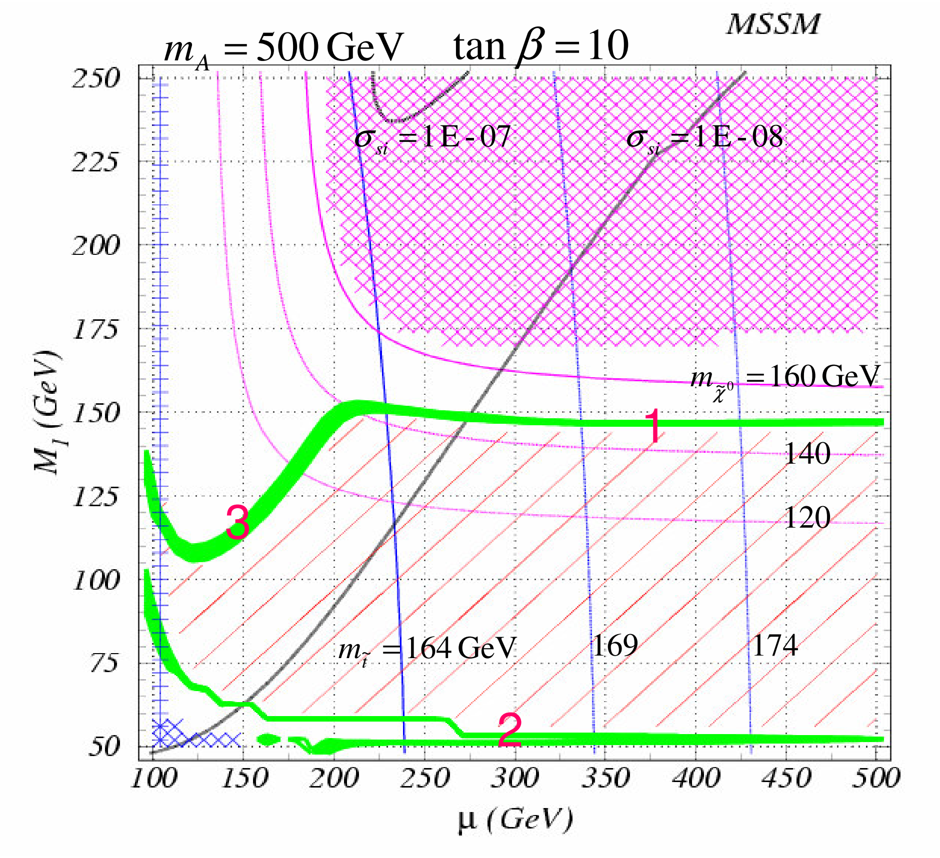
Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

Dark Matter and Electroweak Baryogenesis

• light right handed stop: $m_{\tilde{U}_3} \approx 0$ • heavy left handed stop: $m_{\tilde{Q}_3} \geq 1\,\mathrm{TeV}$

• values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $X_t = \mu / \tan\beta - A_t = 0.3 - 0.5\,\mathrm{m}_{\tilde{Q}_3}$

• the rest of the squarks, sleptons and gluinos order TeV and $\mathrm{M}_2 \cong 2\mathrm{M}_1$



three interesting regions with neutralino relic density compatible with WMAP obs. $0.095 < \Omega_{\mathrm{CDM}} h^2 < 0.129$ (green areas)

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

3. annihilation via Z boson exchange

small μ and M_1

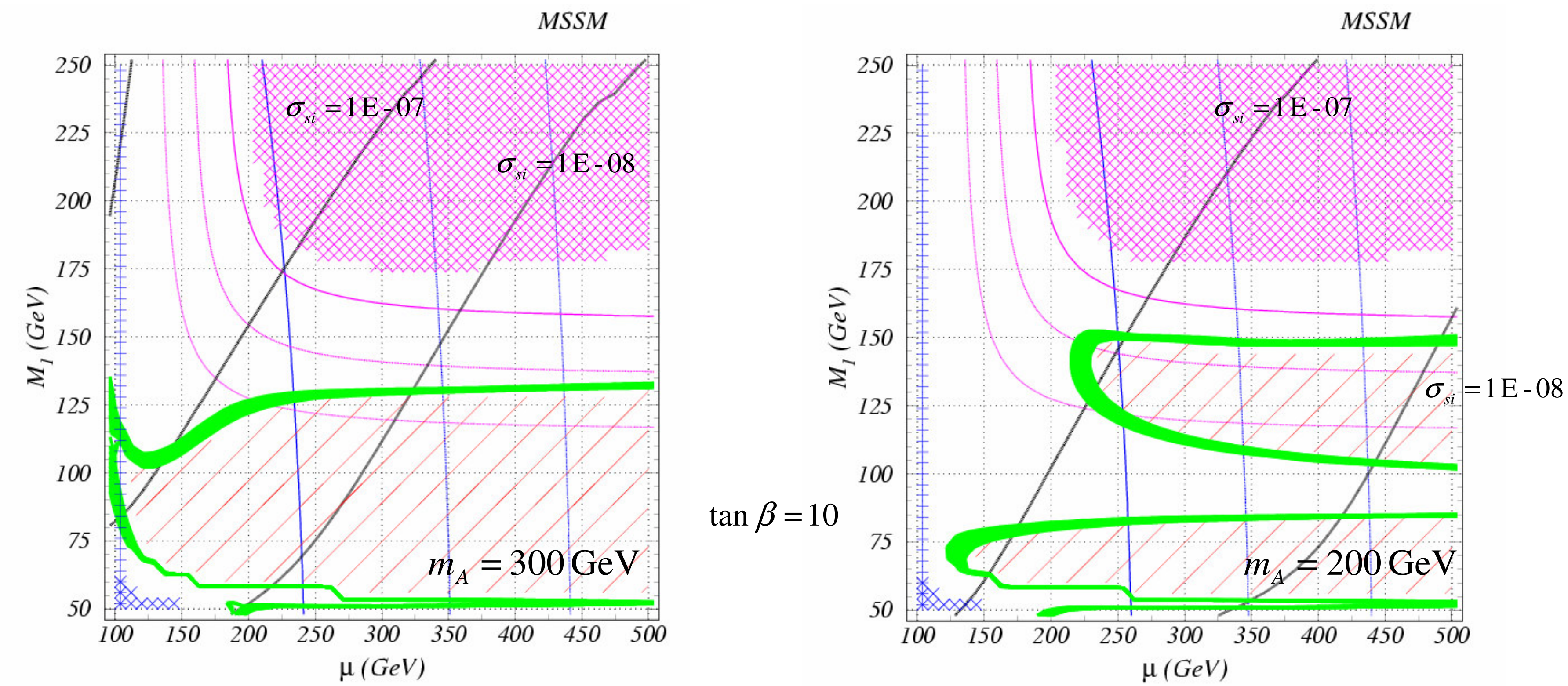
Balazs, MC, Wagner 04

Heavy Higgs mass Effects

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 300\,\mathrm{GeV}$ main effect for values of neutralino mass close to stop mass, allowed region moves away from co-annihilation to lower neutralino masses

- $m_A = 200\,\mathrm{GeV}$ new resonant region due to A,H s-channel (much wider band than for h due to $\tan\beta$ enhanced bb couplings). Stop co-annihilation region reappears.



- larger neutralino-proton scattering cross sections!

Balazs, MC, Wagner

Experimental Tests of Electroweak Baryogenesis and Dark Matter

- Higgs searches:

Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

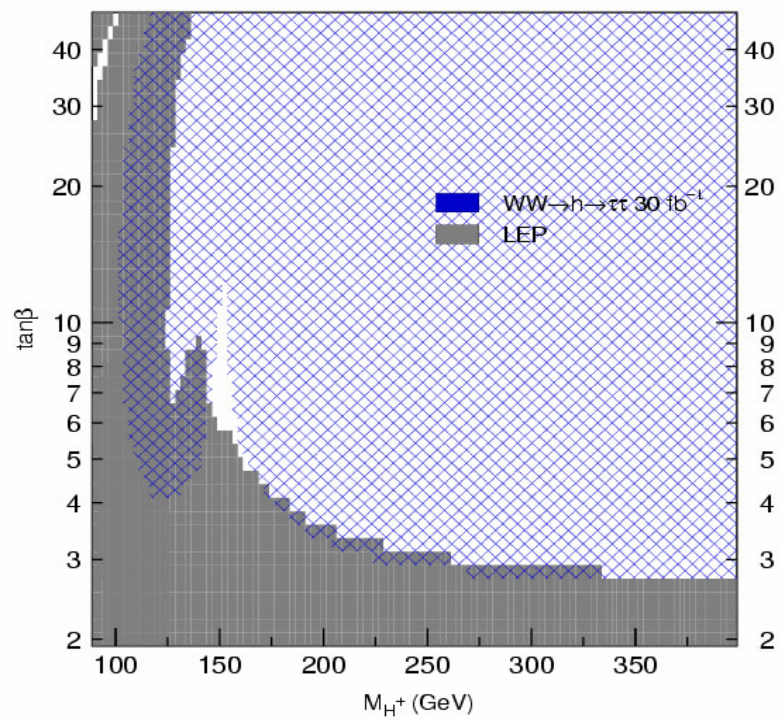
Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \to qqV^*V^* \to qqh$$

$$\text{with } h \to \tau^+\tau^-$$

Maximal mixing scenario



Searches for a light stop at the Tevatron

Light-stop models with neutralino LSP dark matter $\longrightarrow$ $\not{E}_T$ signal

- if $\tilde{t} \longrightarrow c\tilde{\chi}$ decay mode dominant and $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ < 30 GeV:

  trigger on $\not{E}_T$ crucial

$m_{\tilde{\chi}^0} < 100\,\mathrm{GeV}$ and $m_{\tilde{t}} \leq 180\,\mathrm{GeV}$ at reach if $\Delta_{m_{\tilde{t}\tilde{\chi}}} \geq 30\,\mathrm{GeV}$

$m_{\tilde{\chi}^0} \geq 120\,\mathrm{GeV}$ then $m_{\tilde{t}}$ out of reach

- co-annihilation region not at Tevatron reach→
- away from it strong dependence on the neutralino mass

- if $m_{\tilde{t}} > m_{\tilde{\chi}} + m_W + m_b$ (3-body decay)

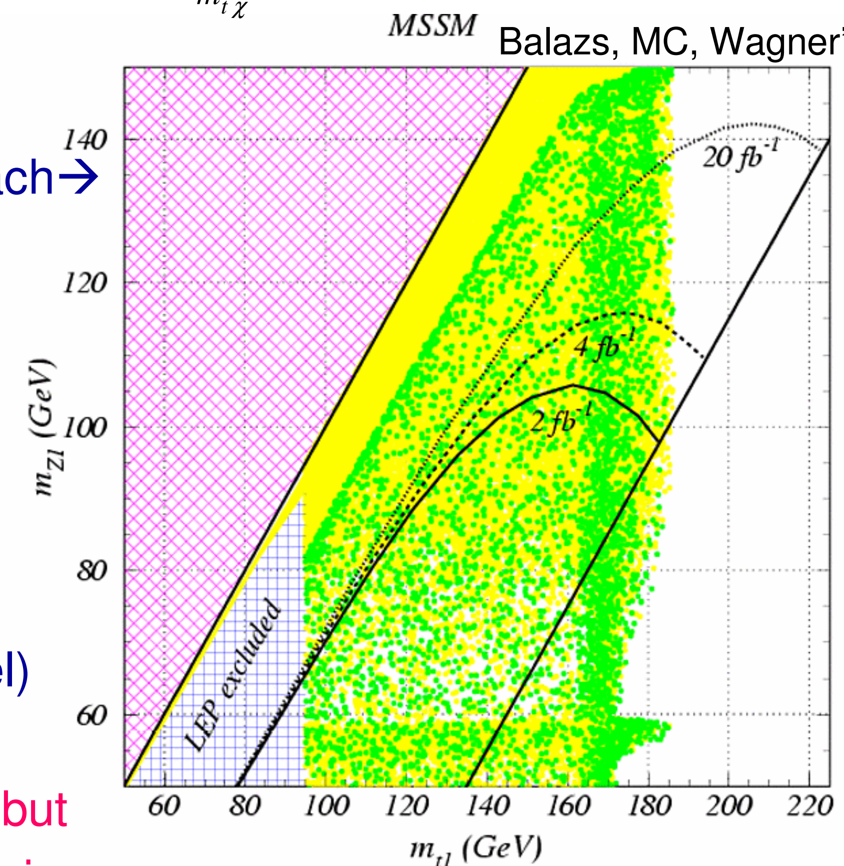
this always happens for

(h-resonance) $m_{\tilde{\chi}^0} \approx m_h/2$

and $m_{\tilde{t}} \geq 140\,\mathrm{GeV}$ no reach

(can search for charginos in trilepton channel)

Balazs, MC, Wagner'04

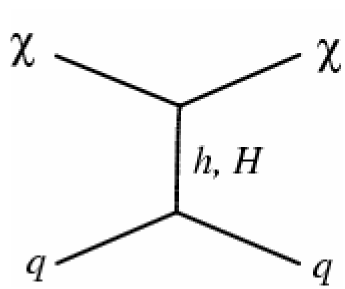


LHC: good for chargino/neutralino searches but also difficulties for stops in co-annihilation region

Direct Dark Matter Detection

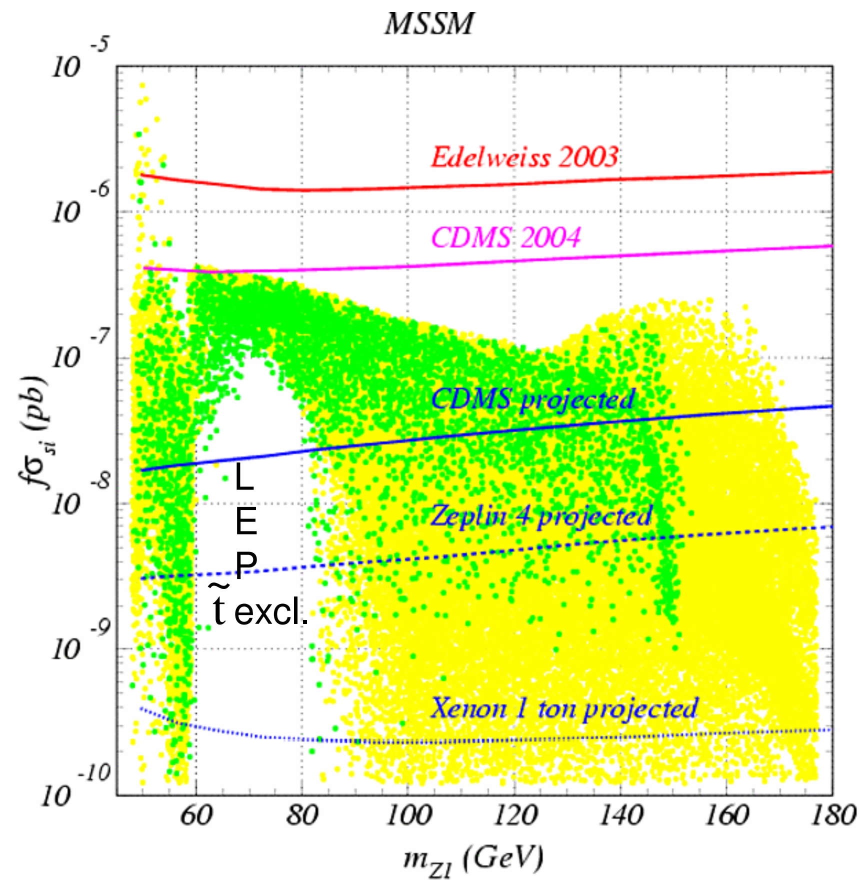
$\not{E}_T$ at colliders $\longrightarrow$ important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



$\longrightarrow$ upper bounds on Spin independent cross sections

Next few years: $\sigma_{SI} \approx 10^{-8}\,\mathrm{pb}$
Ultimate goal: $\sigma_{SI} \approx 10^{-10}\,\mathrm{pb}$



small σ_{si} for large μ : co-annihilation regions

Balazs, MC, Wagner '04

Conclusions

- **Supersymmetry with a light stop** $m_{stop} < m_{top}$ **and**

a SM-like Higgs with $m_h < 120 \text{ GeV}$

$\Downarrow$

opens the window for electroweak baryogenesis and allows for a new region of SUSY parameter space compatible with Dark Matter

also Gaugino and higssino masses of order of the electroweak scale

and moderate CP-odd Higgs mass preferred

new CP violating phases: $\arg(\mu^* M_2) \geq 0.1$ necessary

EWBG and DM in the MSSM → interesting experimental framework

stop-neutralino co-annihilation → challenging for hadron colliders

<u>Tevatron:</u> good prospects in searching for a light stop

<u>LHC:</u> will add to these searches and explore the relevant $\tilde{\chi}^0 / \tilde{\chi}^{\pm}$ spectra

Stop co-annihilation region provides motivation to search in the small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ regime

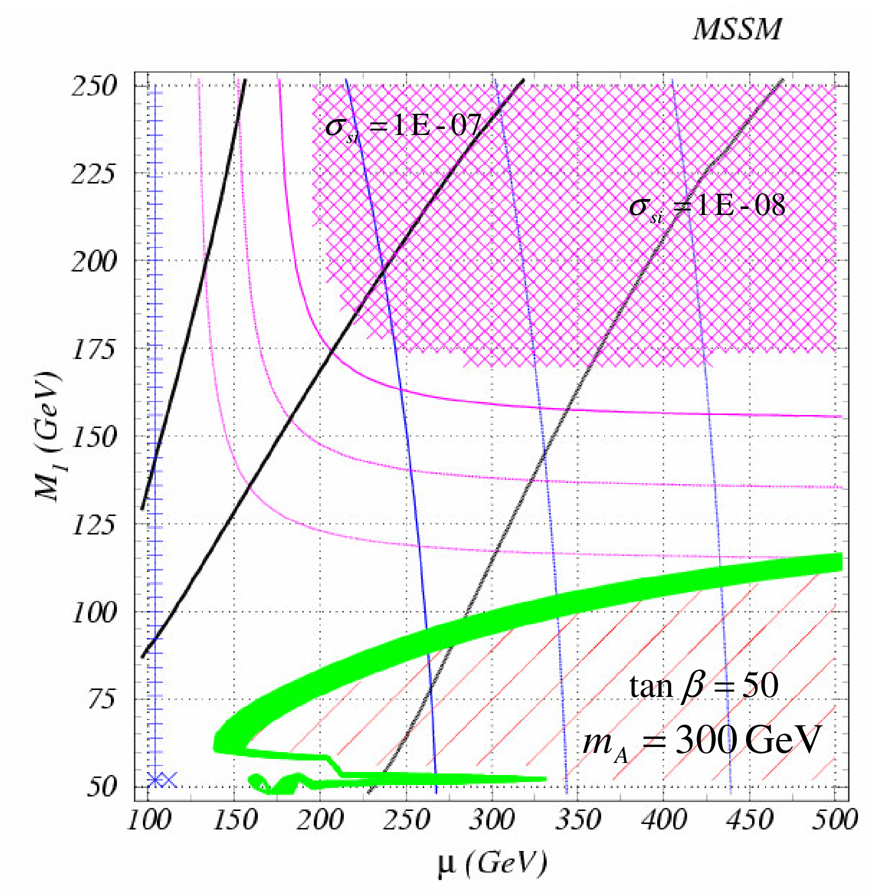
<u>LC</u>: important role in testing this scenario: small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ and nature and composition of light gauginos and stop

<u>Direct Dark Matter detection</u>: nicely complementary to collider searches

$\tan\beta$ Effects on the neutralino relic density

Main effect is via the coupling of the heavy Higgs A,H to bottom quarks

- annihilation cross section grows quadratically with $\tan\beta$



- For sufficiently small heavy Higgs masses and large tan beta:

$$m_A \approx 250--300\,\mathrm{GeV} \qquad \tan\beta \approx 50$$

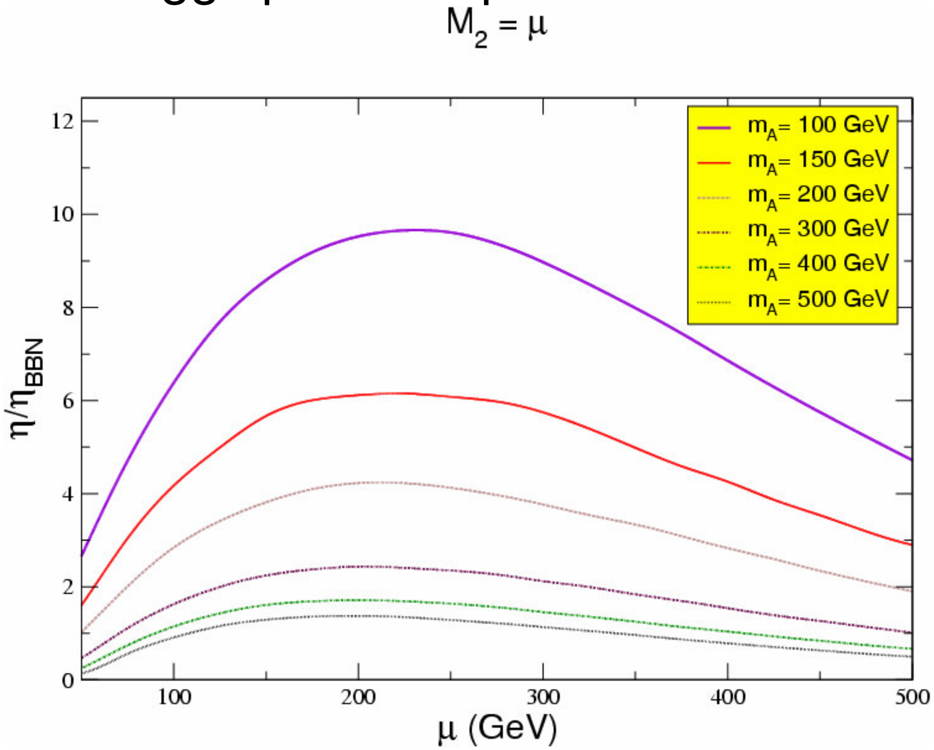
can have dramatic cosequences on the allowed region of parameter space

($m_A \approx 200\,\mathrm{GeV}$ can make the relic density too small over most of the space)

Balazs, MC, Wagner

• New sources of CP violation from the sfermion sector

- Generation of the baryon asymmetry: Charginos with masses μ and M_2 play most relevant role.
- CP-violating Sources depend on $\arg(\mu^* M_2)$
- Higgs profile depends on the mass of the heavy Higgs bosons .



We plot for maximal mixing: within uncertainties, values of $\sin\phi_\mu \geq 0.05$ preferred

Gaugino and Higgsino masses of the order of the weak scale highly preferred

Large CP-odd Higgs mass values are acceptable

M.C., Quiros,. Seco and Wagner '02